PUBLICATIONS OF THE ASTRONOMICAL SOCIETY OF THE PACIFIC, **116**:886–893, 2004 September

Stratospheric Transparency Derived from Total Lunar Eclipse Colors, 1665–1800

RICHARD B. STOTHERS

NASA Goddard Institute for Space Studies, 2880 Broadway, New York, NY 10025; rstothers@giss.nasa.gov

Received 2004 June 24; accepted 2004 July 13; published 2004 August 30

ABSTRACT. A catalog of the observed colors of the totally eclipsed Moon during the period 1665–1800 has been prepared from published contemporary reports. Nearly all of the observations were made from Europe. Usable eclipses number 36 in all, or on average, about one eclipse every 4 years. The hue and intensity of the faint illumination of the Moon's disk during totality yield a measure of the aerosol optical depth of the Earth's stratosphere. Unlike the 19th and 20th centuries, the period under study showed a relatively clear stratosphere at nearly all times. Independent but less direct evidence from Greenland ice cores, which contain an annual record of aerosol fallout from large volcanic eruptions, confirms that this was a period of very few, if any, large stratosphere-penetrating volcanic eruptions.

1. INTRODUCTION

When totally eclipsed on a clear night, the Moon does not wholly vanish, but only dims and reddens. Exactly four centuries ago, Kepler (1604) became the first author to realize that rays of sunlight passing through the Earth's atmosphere are refracted (and scattered) into the shadow cone, illuminating the Moon's face. He also correctly pointed out that increased cloudiness in the atmosphere along the Earth's limb can block more of the sunlight, making the exposed face of the Moon darker. Since the rays reflected off the lunar surface must penetrate the Earth's atmosphere a second time to reach the ground observer, local atmospheric factors of various kinds can influence the visibility and color of the lunar disk: a low altitude of the Moon above the horizon, and related to this, a close proximity in time to dawn or dusk, and also a local cloudiness or general haziness in the air. The importance of these strictly local viewing factors has been recognized since classical antiquity. Yet it was not until after the Krakatau eruption of 1883 that Flammarion (1884) conjectured that a volcanic eruption, by putting a large amount of dust and gas into the upper atmosphere, might also produce darker eclipses. Gradually, all of these qualitative ideas were exploited during the 20th century in order to make estimates of the amount of stratospheric turbidity generated by major volcanic eruptions (Link 1961, 1963; Brooks 1964; Hansen & Matsushima 1966; Matsushima et al. 1966; Matsushima 1967; Hédervári 1980; Keen 1983, 2001).

For several decades before the 1960s, partial lunar eclipses were also used for this purpose. The color of the penumbra, however, comes mainly from solar rays that have traversed the uppermost reaches of the atmosphere, well above the stratosphere. Furthermore, the umbra is always sufficiently dark that to the naked eye, the fully eclipsed portion of the lunar disk appears almost black in contrast to the uneclipsed portion. Only in a total lunar eclipse, during the phase of totality itself, can the color of the illuminated disk become a reliable indicator of stratospheric turbidity. Danjon (1920a, 1920b), de Vaucouleurs (1944), and Vassy (1956) unfortunately included many partial lunar eclipses in order to estimate lunar eclipse brightness as a function of time. Maunder (1921), however, pointed out the enormous error incurred by using partial eclipses, thereby disproving (as Keen [1983] would do much later) Danjon's law stating that lunar eclipses are especially dark for a couple of years after the time of solar minimum in the 11 yr solar activity cycle.

No systematic catalog of lunar eclipse colors before the Krakatau eruption was ever published, except for a sparse catalog for the very early period preceding the year 1000 (Stothers 2002). Although Danjon (1920a) compiled data on about 150 eclipses occurring between the time of Tycho Brahé in the late 16th century and his own time, he never published either his eclipse data or his sources. In the present paper, a comprehensive catalog and analysis of lunar eclipse colors is presented for the period 1665–1800. The results enable us to derive some reliable information about the state of worldwide explosive volcanism during this long period.

2. DATABASE

The time period covered, 1665–1800, opens with the beginning of the publication of modern scientific periodicals—the *Journal des Sçavans* in Paris and the *Philosophical Transactions* in London. It closes at a time when these periodicals, which were general and included all the sciences, were starting to yield to a proliferation of specialty journals. The main scientific journals published during this period have been listed by Gascoigne (1985). Nearly all of the 51 journals he listed that began publication before 1801 have been examined, plus a number of others, including some popular journals that published occasional scientific notes. Searches for lunar eclipse reports in all of these journals have been made by utilizing indexes (annual or cumulative), or else tables of contents, if indexes were unavailable. In addition, a number of scientific monographs, including some published collections of letters, were also examined. Despite these extensive efforts, it is likely that a few eclipse reports were missed. Judging from the character of the nonprofessional eclipse reports appearing in the popular journals, it is probable that little has been lost by entirely ignoring the contemporary almanacs, newspapers, and pamphlets.

Professional astronomers of that period observed lunar eclipses primarily in order to time the crossings of the edge of the Earth's umbra over the Moon's limb and over various prominent lunar features, the ultimate purpose being to determine precise differences of terrestrial longitude between different observing sites. Owing to the obvious need for accurate and clear observations, detailed remarks in the reports were usually added about local meteorological conditions and the degree of visibility of the Moon, including its apparent color during the total phase. Therefore, the potential database stemming from the late 16th century is of quite high quality and, since 1665, also rather abundant.

Lunar eclipse reports accepted for inclusion in the present catalog were required to satisfy certain conditions. The eclipse had to have been total, and totality should have been observed in a clear, dark window of sky, not too near the horizon and not too close in time to dawn or dusk. The Moon's physical appearance during totality must have been explicitly described, at least as to the general visibility of the disk or to the distinguishability of major spots (craters and maria). Ideally, the apparent color of the disk would also be stated. During the historical period covered, the fullest descriptions list in detail the major spots visible, the average color of the disk, and also how the various colors played across the disk in both space and time. Typical features of the shadow on the Moon between the times of immersion and emersion—such as the shift of darkness from one hemisphere to the other, as well as the greater obscurity in the central portion of the disk—although often mentioned, are not of significant value for our present purpose. As long as the eclipse is total, the degree of centrality is of relatively minor importance (Keen 1983). Occasionally, the color and brightness of the rim near mid-totality were noted, providing some additional useful information.

Through a telescope, coloration of the eclipsed Moon appears less intense than with the naked eye. Although nearly all details in published eclipse reports during the period 1665–1800 were based on telescopic observations, the average disk color described was almost certainly seen with the naked eye. For the sake of accuracy, we also quote the color data in the original language used in each report.

Von Oppolzer (1887) has listed the predicted Gregorian dates and other theoretical eclipse data, including the predicted magnitudes, for 81 total lunar eclipses that were potentially visible from somewhere on Earth during the period 1665–1800. In practice, geographical and meteorological constraints considerably reduce this number, since our main reporting area is Europe, although a few reports come from the United States (Williams 1785), Brazil (Dorta 1797, 1799, 1812), China (Hallerstein 1768; Cipolla 1774; Rodrigues 1799), and southern Vietnam (de Loureiro 1814). In all, we have found reports of 36 eclipses for which explicit data on disk visibility and/or color are available. Depending on when and where an eclipse was observed, the date recorded in a contemporary publication can differ from von Oppolzer's catalogued date by up to 11 days, since some countries still used the Julian calendar. We quote here only von Oppolzer's dates.

Citation of authors' names follows modern convention, rather than how the names appeared in the published articles. For example, we refer to Delisle rather than de l'Isle, and Cassini de Thury instead of de Thury. Some latinized names have been returned to the vernacular; e.g., Bullialdus becomes Boulliau, and Blanchinus becomes Bianchini, but the familiar Hevelius has been retained in preference to Hewel. The sole reason for doing so is to have consistency, because variant forms and spellings of certain names occasionally appear in the contemporary literature. Journals were also liable to change their titles, but it seems best in every case to cite the titles as they existed at the time of publication, since this is how libraries list them today. The titular year of the volume is always cited, rather than the year in which the volume was actually printed.

3. DANJON'S SCALE

Colors other than red can also appear during a total lunar eclipse, especially near the Moon's rim. Although this fact has been known since ancient times, modern methods of reporting eclipse colors have ranged from traditional, simple visual descriptions (e.g., Herschel 1870; Moore 1963; Flammarion & Danjon 1964) to more objective photometric measurements (e.g., Dyson & Woolley 1937; Link 1963; Matsushima & Zink 1964; Hansen & Matsushima 1966).

In the case of eclipses for which only subjective descriptions are available, an intermediate method of quantifying the information was devised by Danjon (1920a, 1920b), who focused on the reported hue and intensity of the average disk color, in addition to the described color of the rim, in order to derive an approximate scale of luminosity L. The Danjon scale of lunar eclipse brightness, often used by amateurs as well as by some professional astronomers, runs from zero to 4:

$L = 0$: Very dark eclipse. Moon almost invisible.

$L = 1$: Dark eclipse, gray or brownish. Details difficult to make out.

$L = 2$: Deep red or russet eclipse. Very dark at the center of the shadow. Rather bright rim.

$L = 3$: Brick red eclipse. Shadow often with a rather bright gray or yellow rim.

$L = 4$: Very bright copper red or orange eclipse. Very luminous, bluish rim.

Although this scale was originally constructed to include observations of partial eclipses, it holds up very well for the all-important phase of totality in total eclipses (Keen 1983). If the amount of the excess atmospheric visual optical depth τ_{vis} has to be estimated, the data and discussion in Keen (1983) suggest the following average values: $\tau_{\mathrm{vis}} = 0.10$ (or greater), 0.04, 0.02, 0.01, and 0.00, for $L = 0$, 1, 2, 3, and 4, respectively.

4. CATALOG

Table 1 contains our summary of the data on visibility and color of totally eclipsed lunar disks. Estimates of the disk brightness L in Danjon's scale are also listed. It is not always easy to make these estimates. Local meteorological conditions can greatly change the apparent color and intensity of the disk's illumination from what would be seen in a perfectly cloud-free sky with low humidity. The present author has seen the eclipsed Moon appear blue, purple, or chocolate brown through a thick haze. There is also the personal equation of the individual observer, which is often revealed by a unique mode of expression. For instance, the description "rougeâtre" (reddish) was routinely employed by many of the French observers, such as G. F. Maraldi, du Chatelard, Le Monnier, and Cassini de Thury, whereas J. Cassini characteristically wrote "rouge" (red) and "brun" (brown) in various combinations. Portuguese observer B. S. Dorta always wrote "ferro em braza" (glowing iron). If, however, the color is not characterized in a meaningful way, we have simply assigned a default value of $L = 4$. Puzzling cases that present discrepancies in the reported colors are tagged with an asterisk in Table 1 and are discussed here.

4.1. 1703 December 23

Different observers of this eclipse gave widely varying descriptions of the intensity of the ruddiness seen across the disk. They all agreed, however, that totality began with a dark leaden gray color and ended with the Moon becoming invisible as dawn came on (Cassini 1704). Between these times, observers at separate sites in France saw a redness near the limb, an overall dark red or brown color, a vague overall reddishness, and even a very bright red color. Taking a hint from Cassini, one commentator (Anonymous 1706) attributed the apparent variations to different amounts of water vapor in the atmosphere at different sites. In Italy, Bianchini (1737) saw the eclipse as very bright. The true color was evidently bright red (Johnson 1896). This may be the unidentified eclipse for which Flamsteed (1718), observing in England, reported that he could not see the Moon, even though the sky appeared to be perfectly clear.

4.2. 1729 August 9

Many observers noted the deep red color of this eclipse at its start and at its end. At mid-totality, however, the eclipse was universally described as being very much darker, according to those who commented on the middle phase (Cassini 1729b; Godin 1729b; Rost 1734; Celsius 1737). Apparently, this was a rather dark eclipse.

4.3. 1732 December 1 and 1743 November 2

During the course of these two reddish eclipses, the Moon was described by du Chatelard (1733, 1743) as having grown exceedingly dark, verging on invisibility, especially around mid-totality. Although we have no independent testimony concerning the second eclipse, the first one appeared completely normal, according to many other observers (Table 1). Indeed, du Chatelard (1729b) mentioned that the Moon, during a slightly earlier eclipse on 1729 February 13, alternated between a very reddish color and invisibility due to passing clouds. We are therefore probably justified in regarding his observations of the two later eclipses as having been affected similarly by unreported cloudiness.

4.4. 1761 May 18

This is the famous 18th century eclipse in which the Moon apparently vanished from a clear sky. This total eclipse has been much commented on in modern times (Flammarion 1884; Lynn 1901; Johnson 1896, 1903; Link 1961, 1963; Moore 1963; Hédervári 1980; Maclean 1984), its darkness invariably being attributed to some unknown volcanic eruption, perhaps Jorullo in Mexico in 1759. The principal evidence comes from Wargentin's (1761) eclipse report, which appears to be backed up by several similar contemporary reports (Table 1). All accounts of the Moon's vanishing, however, were based on observations made in Sweden, Finland, or northwestern Russia, with the Moon located near the horizon. In the Netherlands, Lulofs (1762) reported only that the Moon had a paler color than normal. Still farther south, in northern France, Bouin & Dulague (1774) described the disk as reddish, but somewhat brighter at the center; however, they noted that off and on, the sky was cloudy. Clearly, this was a normal eclipse, but was viewed through haze and cloud that became thicker at higher geographical latitudes. Although Link (1961) had previously mentioned the French report, he later regarded this eclipse as having been truly dark, perhaps because he was unaware of the critically important Dutch report made by Lulofs (Link 1963).

4.5. 1772 October 11

French observers described the color of the Moon as being dark gray, like "light China ink," but they pointed out that the Moon lay close to the horizon (de Luynes 1772; Messier 1772). In Germany and northwestern Russia, the eclipse was seen more clearly as deep red (Inochodzow 1775; Wolf 1781).

4.6. 1783 March 18 and September 10

Chevalier (1783, 1788) has contrasted these two deep central eclipses occurring in the same year. The first eclipse appeared reddish, with the lunar spots very visible, while the second one

TABLE 1
Catalog of Total Lunar Eclipse Colors, 1665–1800

Date	*L*	Description of Disk	References
1671 Sep 18	3	Visible	Boulliau 1671
		Very red	Flamsteed 1671
1675 Jan 11	3	Red brown (rouge brune)	Cassini et al. 1675a, 1675b
1675 Jul 7	4	Visible	Anonymous 1675
		Ashen around limb	Flamsteed 1675
1682 Feb 21	3	Blood red or rusty (rubidus, sanguineus, aut rubiginosus)	Hevelius 1682, 1683
1685 Dec 10	4	Ruddy (rubicundus)	Hevelius 1685
		Copper (cuivre)	Cassini 1686
		Pale ruddy (subrufo pallido)	Bianchini 1686
1703 Jun 29	3	Reddish (rougeâtre), lemon yellow (jaune de citron)	Laval 1703, 1719
		Ruddy (rubicundiori)	Bianchini 1737
*1703 Dec 23	4	Gray and dark (grise et sombre)	de Clapiés 1710; Cassini 1704
		Dark red (rouge obscur)	Laval 1719; Cassini 1704
		Brown (brun), very bright red (rouge fort clair), reddish (rougeâtre)	Cassini 1704; Anonymous 1704, 1706
1707 Apr 17	3	Reddish (rutilo)	Jacobs & Scheuchzer 1707
		Reddish (rougeâtre)	Cassini & Maraldi 1707
		Reddish (rubet)	Wurzelbau 1710; Bianchini 1737
		Ruddy (murice vel subrufo)	Hecker 1710
		Very red (fort rouge)	La Hire 1707a, 1707b
1718 Mar 16	3	Glowing iron (candentis ferri)	Hallerstein 1768
1718 Sep 9	3	Dark reddish (obscuro et subrubro)	Poleni & Morgagni 1718, 1724; Bianchini 1737
		Reddish (rubescenti), very bright (clarissime)	Manfredi & Manfredi 1718, 1724
		Reddish (rougeâtre)	Maraldi 1718; Bianchini 1718
		Fiery red (rouge ardente)	Cassini 1718
		Browner (plus brun) at center	La Hire 1718
		Very dark red (rouge fort obscur)	Laval 1719
		Rusty (rubigine) with yellow (flavo) limb	Lindheim 1730
1722 Jun 29	3	Reddish (rougeâtre)	Maraldi 1722
		Reddish brown (brun tirant sur le rouge)	Cassini 1722
1725 Oct 21	3	Reddish (rubescens)	Bianchini 1726, 1737
		Ruddy (subrufus)	Kirch 1727; Hallerstein 1768
1729 Feb 13	3	Quite ruddy (admodum rubicunda)	Poleni 1729a
		Reddish (subrubro)	Bianchini 1737
		Very reddish (fort rougeâtre)	du Chatelard 1729a
		Reddish (rougeâtre)	Maraldi 1729; de Louville 1729
		Red brown (rouge brun)	Cassini 1729a; Godin 1729a
*1729 Aug 9	2	Invisible	Cassini 1729b; Godin 1729b
		Quite black (admodum nigra)	Celsius 1737
		Coppery (cuprea), dark (furvum)	Rost 1734
		Ruddy (rubicundus)	Kirch 1730
		Very reddish (fort rougeâtre)	du Chatelard 1729b
		Plum red (prunae rubuit)	Weidler 1729
1732 Jun 8	3	Red (rufo)	Hallerstein 1768
*1732 Dec 1	3	Visible	Poleni 1729b; Godin 1732
		Red (rouge)	Borgondio 1733
		Red (rouge), near-black (tirant sur le noir)	du Chatelard 1733
		Reddish (subruber)	Marinoni 1733
		Red brown (rouge brun)	Cassini 1732
1736 Mar 27	3	Visible	Anonymous 1736; Cassini 1736a
		Feebly reddish (rougeâtre si faible)	Le Monnier 1736
		Reddish (subruber)	Francz 1736
		Glowing-iron red (candentis ferri rubebat)	Bevis 1737
1736 Sep 20	3	Visible	Francz 1737
		Reddish (rougeâtre)	Cassini 1736b
1740 Jan 13	3	Red (rubrum)	Schoenwald 1754
*1743 Nov 2	3	Reddish (rougeâtre), deep iron gray (gris de fer foncé)	du Chatelard 1743
1747 Feb 25	3	Reddish (rougeâtre)	Cassini 1747

TABLE 1. (*Continued*)
CATALOG OF TOTAL LUNAR ECLIPSE COLORS, 1665–1800

Date	*L*	Description of Disk	References
1750 Jun 19 ………	3	Visible	de Fouchy 1750; Heinsius 1750
		Reddish (rougeâtre)	Cassini de Thury 1750
		Glowing-iron red (rutilo candentis ferri)	Mayer 1752
		Deep red (rouge foncé)	Estéve 1755
		Reddish (rougeâtre), smoky dark (enfumé)	Le Monnier 1750
1750 Dec 13 ……..	3	Red (rouge)	Delisle 1750
		Red brown (rouge brun)	Cassini de Thury & Maraldi 1750
1758 Jan 24 ………	4	Visible	Anonymous 1758
*1761 May 18 ……	3	Invisible	Wargentin 1761; Strömer & Wargentin 1762; Planmann 1762; Hellant 1762; Aepinus 1762
		Paler than normal (bleeker)	Lulofs 1762
		Reddish (rougeâtre)	Bouin & Dulague 1774
1761 Nov 12 ……..	3	Glowing iron (ferri candentis)	Cipolla 1774
		Paler than normal (tenui at naturali)	de Loureiro 1814
*1772 Oct 11 …….	3	Visible	Bernoulli 1772
		Dark reddish (fusco ad subrubrum)	Inochodzow 1775
		Very red (intense rubrum)	Wolf 1781
		Light China ink gray (gris)	Messier 1772; de Luynes 1772
1776 Jul 31 ………	3	Visible	de Fouchy 1776; Jeaurat 1776; Wollaston 1785; Toaldo 1786
		Reddish (rougeâtre)	Cassini de Thury 1776; Cassini 1788
		Reddish (röthliche)	Helfenzrieder & Bernoulli 1779
		Very red (rouge considérable)	Messier 1776
		Dark ruddy (obscure rubicundo)	Wargentin 1780
1779 Nov 23 ……..	3	Reddish (röthlich), glowing coal (glühende Kohle)	Köhler 1784
		Dark blood red (fusca ac sanguinolenta)	Rodrigues 1799
* 1783 Mar 18 ……	3	Red (rouge)	Messier 1783
		Reddish (rougeâtre)	Chevalier 1783
* 1783 Sep 10 ……	2	Visible	Anonymous 1783; Wollaston 1785
		Reddish (rougeâtre)	Mallet 1782; Messier 1783
		Dark red (rouge obscur)	Chevalier 1788
		Dusky copper	Williams 1785
		Glowing iron (ferro em braza)	Dorta 1797
1787 Jan 3 ……….	2	Dark reddish (vermelho escuro)	Velho 1799
		Dark red (dunkelrød), coppery (kobberagtig)	Bugge 1788
		Glowing iron (ferro em braza)	Dorta 1812
1790 Apr 28 ……..	3	Visible	Villas-Boas 1799
		Red (rother)	Bode 1794a
		Reddish (röthlich)	Zach 1794
		Fiery red (feuerrother)	Beitler & Bernoulli 1794
		Glowing iron (ferro em braza)	Dorta 1799
*1790 Oct 23 …….	4	Visible	Schröter 1794
		Red (røde)	Bugge 1793
		Red (rother) with bluish (bläuliche) limb	Bode 1794b
		Light China ink, mixed with reddish (rougeâtre) parts	Messier 1790
		Bright red points	Herschel 1792
1794 Feb 14 ………	4	Visible	Darquier in Lalande 1801
*1797 Dec 4 ……..	3	Reddish (röthlicher)	Bode 1801
		Dark red (rouge obscur), bright yellow (jaune assez clair)	Flaugergues in Lalande 1798
		Faint yellowish copper	Lofft 1797
		Glimmering red points (röthlich glimmende Pünktchen)	Schröter & Harding 1801

seemed dark red, with the spots less easily detected. Messier (1783) called the first eclipse red and the second one reddish like Mars. The deep red color of the second eclipse was also noticed by others (Table 1). The cause of the slight darkening may have been the presence of tropospheric (short lived) and stratospheric (long lived) aerosols generated by the Laki fissure eruption in Iceland between the months of 1783 June and 1784 February. Since this unevenly distributed aerosol veil did not extend south of about 30° north (Stothers 1996a; Demarée et al. 1998), the fraction of the Earth's surface that was at least partly shrouded would have been only about 40%. Although another far-northern eruption, Alaska's Katmai in 1912 June, also delivered an aerosol veil only as far south as about 30° north (Stothers 1996b), the deep central eclipse of

1913 March 22 was very dark (de Vaucouleurs 1944). We infer from this comparison that Laki's aerosols, unlike Katmai's, were in large part tropospheric; this conclusion agrees with a detailed volcanological and meteorological reconstruction of the Laki eruption (Thordarson & Self 2003).

4.7. 1790 October 23

Seen as a whole, the disk appeared red, with a bluish rim (Bugge 1793; Bode 1794b). Under telescopic magnification, however, the disk had the color of "light China ink," mixed here and there with a reddish, bloodlike color (Messier 1790). Herschel (1792) actually counted more than 150 bright red, luminous points across the disk. This is, in fact, the usual appearance of the totally eclipsed Moon as seen through a telescope, the irregularities of the lunar surface creating the red highlights (Flammarion & Danjon 1964).

4.8. 1797 December 4

Bode (1801) called this eclipse reddish, but Flaugergues (Lalande 1798) observed that it ranged from dark red to rather bright yellow, a mix of colors that was corroborated by Lofft (1797). Numerous reddish points glimmered on the darkened surface (Schröter & Harding 1801), just as Herschel (1792) had described for the eclipse of 1790 October 23.

5. CONCLUSION

Of the 36 observed total lunar eclipses during the period 1665–1800 for which we have adequate information, none appears to have been a truly dark eclipse. A few were slightly dark eclipses, but only one yielded an apparent false alarm (that of 1761 May 18). The very low incidence of false alarms agrees well with modern observations for the period following 1883 (Link 1961; Keen 1983, 2001); it also indirectly supports the validity of our available statistics on dark lunar eclipses for the early medieval period, 400–1000 (Stothers 2002). Contrary to a prediction by Bicknell (1983), the Maunder minimum of solar activity from 1645 to 1715 was not associated with a long series of dark total lunar eclipses.

Lists of known volcanic eruptions that might have been large enough to have had a measurable atmospheric impact have been published by Russell (1888), Lamb (1970), and Newhall & Self (1982), among others. For the period 1665–1800, the most promising eruptions were those of Laki (1783), Katla (1755), and Tarumai (1667 and 1739). These three volcanoes, however, lie at high latitudes in Iceland or Japan; therefore, any spreading of their aerosol veils is unlikely to have extended farther south than about 30° north. Although our eclipse data are inadequate to form a judgment about Katla (1755), this fissure eruption was definitely smaller than Laki (1783), which produced only a slight eclipse darkening. Likewise, because Tarumai (1739) led to no noticeable eclipse darkening in 1740, it too may not have been a large stratosphere-penetrating eruption. We can say nothing, however, about the other Tarumai eruption, in 1667.

An indirect measure of past atmospheric disturbances due to volcanic aerosols can be independently acquired by actually collecting the acid residues of the aerosols. In the time that the aerosols are still suspended in the atmosphere, they are rapidly carried far and wide by global winds until the particles finally settle to the ground, which could be a matter of days for the troposphere, or up to a few years for the stratosphere (e.g., Robock 2000). Those aerosols that fall onto the polar caps become incorporated into that year's annual ice layers. Cores later extracted from the polar ice caps can be dated by counting the number of ice layers downward to clearly identifiable horizons where the acidity due to the sulfate aerosols is especially high.

Data from two deep Greenland ice cores have been compared and discussed by Clausen et al. (1997). A large acid "signal" appears in a layer dated at 1783, doubtless due to the nearby Laki eruption, and a smaller signal at 1668, perhaps due to Tarumai. Other acid signals in this period are not trusted by Clausen et al. as being necessarily anything other than background noise. Zielinski et al. (1994) and Zielinski (1995) have detected large acid signals in a third Greenland ice core in eight layers within the period 1665–1800. Although all of these signals have possible dating errors of ± 1 yr, two of them occur at (or near) 1784 and 1668, just as in the case of the other Greenland ice cores.

Besides the Laki acid signal, three others can be compared with known eruptions and our lunar eclipse data. One at 1738 ± 1 could be associated with the Tarumai (1739) eruption, but there was no noticeable eclipse darkening in 1740. The acid signal at 1731 ± 1 might have come from the continuing eruption of Lanzarote in the Canary Islands (1730–1736), although the apparently normal appearances of the eclipses of 1732 and 1736 would suggest little stratospheric injection of aerosols. A third acid signal at 1728 ± 1 might have been due to the Oraefajokull, Iceland (1727), eruption; however, the first eclipse of 1729 appeared perfectly normal. Since the second eclipse of 1729 was slightly darker, another eruption somewhere else in the world might have occurred after February of that year. All in all, it seems that the production of aerosols by volcanoes was mostly a tropospheric phenomenon in this period.

To conclude: the long period of 1665–1800 appears to have been unusually free of large stratosphere-penetrating volcanic eruptions. This contrasts with the modern period beginning in 1800. Despite the poorer temporal resolution of the lunar eclipse method compared to the ice core method, total lunar eclipses actually provide a much more direct and sensitive probe of stratospheric transparency, when they are available.

Libraries supplying the necessary historical materials were the Columbia University Libraries, New York Public Library, American Museum of Natural History Library, and Bibliothèque Nationale de France. Special interlibrary loan assistance was provided by Zoe Wai and Josefina Mora. Overall support of the present work came from the NASA Climate Research Program.

REFERENCES

Aepinus, F.V. T. 1762, Novi Commentarii Acad. Sci. Imp. Petropolitanae, 9, 496
Anonymous 1675, J. Sçavans (Paris), 1675, 215
———. 1704, Histoire Acad. R. Sci. (Paris), 1704, 58
———. 1706, Acta Eruditorum, 25, 439
———. 1736, London Mag., 5, 130
———. 1758, Gentleman's Mag., 28, 7
———. 1783, London Mag. (New Series), 1, 345
Beitler, W. G. F., & Bernoulli, J. 1794, Astron. Jahrbuch, 19, 255
Bernoulli, J. 1772, Nouveaux Mémoires Acad. R. Sci. Berlin, 1772, 293
Bevis, J. 1737, Philos. Trans., 40, 16
Bianchini, F. 1686, Acta Eruditorum, 5, 52
———. 1718, Mémoires Acad. R. Sci. (Paris), 1718, 327
———. 1726, Philos. Trans., 34, 179
———. 1737, Astronomicae ac Geographicae Observationes Selectae Romae (Verona: Thomas)
Bicknell, P. 1983, J. Brit. Astron. Assoc., 93, 160
Bode, J. E. 1794a, Astron. Jahrbuch, 19, 108
———. 1794b, Astron. Jahrbuch, 19, 109
———. 1801, Astron. Jahrbuch, 26, 97
Borgondio, H. 1733, Mémoires Trévoux, Mar, 547
Bouin, J. T., & Dulague, V. F. N. J. 1774, Mémoires Acad. R. Sci. Divers Savans, 1774, 459
Boulliau, I. 1671, Philos. Trans., 6, 2272
Brooks, E. M. 1964, S&T, 27, 346
Bugge, T. 1788, Skrifter Nye Samling Kongl. Danske Vid. Sel., 3, 517
———. 1793, Skrifter Nye Samling Kongl. Danske Vid. Sel., 4, 545
Cassini, G. D. 1686, J. Sçavans (Paris), 1686, 317
Cassini, G. D., Picard, J., & Roemer, O. 1675a, J. Sçavans (Paris), 1675, 44
———. 1675b, Philos. Trans., 10, 257
Cassini, J. 1704, Mémoires Acad. R. Sci. (Paris), 1704, 14
———. 1718, Mémoires Acad. R. Sci. (Paris), 1718, 279
———. 1722, Mémoires Acad. R. Sci. (Paris), 1722, 169
———. 1729a, Mémoires Acad. R. Sci. (Amsterdam), 1729, 6
———. 1729b, Mémoires Acad. R. Sci. (Amsterdam), 1729, 487
———. 1732, Mémoires Acad. R. Sci. (Amsterdam), 1732, 664
———. 1736a, Mémoires Acad. R. Sci. (Paris), 1736, 184
———. 1736b, Mémoires Acad. R. Sci. (Paris), 1736, 313
———. 1747, Mémoires Acad. R. Sci. (Paris), 1747, 459
Cassini, J., & Maraldi, G. F. 1707, Mémoires Acad. R. Sci. (Paris), 1707, 168
Cassini, J. D. 1788, Extrait des Observations Astronomiques et Physiques (Paris: Imprimerie Royale), 198
Cassini de Thury, C. F. 1750, Mémoires Acad. R. Sci. (Paris), 1750, 236
———. 1776, Mémoires Acad. R. Sci. (Paris), 1776, 433
Cassini de Thury, C. F., & Maraldi, G. D. 1750, Mémoires Acad. R. Sci. (Paris), 1750, 272
Celsius, A. 1737, Acta Lit. Sci. Sueciae, 4, 243
Chevalier, J. 1783, Mémoires Acad. Imp. R. Bruxelles, 4, 323
———. 1788, Mémoires Acad. Imp. R. Bruxelles, 5, 13
Cipolla, L. 1774, Philos. Trans., 64, 43
Clausen, H. B., et al. 1997, J. Geophys. Res., 102, 26707
Danjon, A. 1920a, Comptes Rendus Acad. Sci., 171, 1127
———. 1920b, Comptes Rendus Acad. Sci., 171, 1207
de Clapiés, J. 1710,. Mémoires Trévoux, May, 841
de Fouchy, J. P. G. 1750, Mémoires Acad. R. Sci. (Paris), 1750, 239
de Fouchy, J. P. G. 1776, Mémoires Acad. R. Sci. (Paris), 1776, 436
Delisle, J. N. 1750, Mémoires Acad. R. Sci. (Paris), 1750, 343
de Loureiro, J. 1814, Memorias Acad. Real Sci. Lisboa, 3(2), 1
de Louville, J. E. 1729, Mémoires Acad. R. Sci. (Amsterdam), 1729, 15
de Luynes, P. d'A. 1772, Mémoires Acad. R. Sci. (Paris), 1772, 378
Demarée, G. R., Ogilvie, A. E. J., & Zhang, D. 1998, Clim. Change, 39, 727
de Vaucouleurs, G. 1944, Comptes Rendus Acad. Sci., 218, 655
Dorta, B. S. 1797, Memorias Acad. Real Sci. Lisboa, 1, 325
———. 1799, Memorias Acad. Real Sci. Lisboa, 2(1), 193
———. 1812, Memorias Acad. Real Sci. Lisboa, 3(1), 68
du Chatelard. 1729a, Mémoires Trévoux, Nov, 1937
———. 1729b, Mémoires Trévoux, Nov, 2067
———. 1733, Mémoires Trévoux, Mar, 550
———. 1743, Mémoires Trévoux, Nov, 2888f
Dyson, F., & Woolley, R. v. d. R. 1937, Eclipses of the Sun and Moon (Oxford: Clarendon), 30
Estéve. 1755, Mémoires Acad. R. Sci. Divers Savans, 1755, 315
Flammarion, C. 1884, L'Astronomie, 3, 401
Flammarion, G. C., & Danjon, A. 1964, The Flammarion Book of Astronomy (New York: Simon & Schuster), 137
Flamsteed, J. 1671, Letter 69, in The Correspondence of John Flamsteed, the First Astronomer Royal, ed. E. G. Forbes (Philadelphia: Inst. Physics, 1995), 1, 110
———. 1675, Philos. Trans., 10, 371
———. 1718, Letter 1486, in The Correpondence of John Flamsteed, the First Astronomer Royal, ed. E. G. Forbes (Philadelphia: Inst. Physics, 1995), 2, 872
Francz, J. 1736, Mémoires Trévoux, Aug, 1905
———. 1737, Mémoires Trévoux, Feb, 372f
Gascoigne, R. M. 1985, A Historical Catalogue of Scientific Periodicals, 1665–1900, with a Survey of Their Development (New York: Garland)
Godin, L. 1729a, Mémoires Acad. R. Sci. (Amsterdam), 1729, 11
———. 1729b, Mémoires Acad. R. Sci. (Amsterdam), 1729, 489
———. 1732, Mémoires Acad. R. Sci. (Amsterdam), 1732, 667
Hallerstein, A. 1768, Observationes Astronomicae ab Anno 1717 ad Annum 1752 Pekini Sinarum Factae (Vienna: Trattnern)
Hansen, J. E., & Matsushima, S. 1966, J. Geophys. Res., 71, 1073
Hecker, C. G. 1710, Miscellanea Berolinensia Increm. Sci., 1, 245
Hédervári, P. 1980, J. Assoc. Lunar Planet. Obs., 28, 158
Heinsius, G. 1750, Novi Commentarii Acad. Sci. Imp. Petropolitanae, 3, 424
Helfenzrieder, J. E., & Bernoulli, J. 1779, Astron. Jahrbuch, 4, 43
Hellant, A. 1762, Abhand. König. Schwedische Akad. Wiss., 24, 331
Herschel, J. F. W. 1870, Outlines of Astronomy (New York: Sheldon), 224
Herschel, W. 1792, Philos. Trans., 82, 27
Hevelius, J. 1682, Acta Eruditorum, 1, 109
———. 1683, Philos. Trans., 13, 146
———. 1685, Philos. Trans., 15, 1256
Inochodzow, P. 1775, Novi Commentarii Acad. Sci. Imp. Petropolitanae, 20, 614

Jacobs, J., & Scheuchzer, J. 1707, Philos. Trans., 25, 2394
Jeaurat, E.-S. 1776, Mémoires Acad. R. Sci. (Paris), 1776, 438
Johnson, S. J. 1896, Historical and Future Eclipses (London: Parker)
———. 1903, MNRAS, 63, 400
Keen, R. A. 1983, Science, 222, 1011
———. 2001, Bull. Global Volcanism Netw., 26 (5), 17
Kepler, J. 1604, Astronomiae Pars Optica (Frankfurt: Marnius), 267
Kirch, C. 1727, Miscellanea Berolinensia Increm. Sci., 3, 228
———. 1730, Observationes Astronomicae Selectiores in Observatorio Regio Berolinensi Habitae (Berlin: Haude), 20
Köhler, J. G. 1784, Astron. Jahrbuch, 9, 146
La Hire, P. de 1707a, Histoire Acad. R. Sci. (Paris), 1707, 81
———. 1707b, Mémoires Acad. R. Sci. (Paris), 1707, 172
———. 1718, Mémoires Acad. R. Sci. (Paris), 1718, 283
Lalande, J. J. L. de 1798, Mélanges d'Astronomie (Paris: Duprat), 321
———. 1801, Histoire Céleste Française (Paris: Imprimerie de la Republique), 1, 415
Lamb, H. H. 1970, Philos. Trans. R. Soc., A, 266, 425
Laval, A. F., 1703, Histoire Acad. R. Sci. (Paris), 1703, 77
———. 1719, Mémoires Trévoux, Nov, 141
Le Monnier, P.-C. 1736, Mémoires Acad. R. Sci. (Paris), 1736, 261
———. 1750, Mémoires Acad. R. Sci. (Paris), 1750, 151
Lindheim, S. 1730, Acta Lit. Sci. Sueciae, 3, 38
Link, F. 1961, Studia Geophys. Geod., 5, 64
———. 1963, Adv. Astron. Astrophys., 2, 87
Lofft, C. 1797, Monthly Mag., 4, 423
Lulofs, J. 1762, Verhand. Hollandsche Maat. Weten. Haarlem, 6, 866
Lynn, W. T. 1901, Remarkable Eclipses (London: Sampson Low, Marston), 49
Maclean, A. D. I. 1984, J. Brit. Astron. Assoc., 94, 263
Mallet, J. A. 1782, Acta Acad. Sci. Imp. Petropolitanae, 6(1), 339
Manfredi, E., & Manfredi, G. 1718, Giornale Lett. Italia, 31, 309
———. 1724, Philos. Trans., 33, 74
Maraldi, G. D. 1729, Mémoires Acad. R. Sci. (Amsterdam), 1729, 1
Maraldi, G. F. 1718, Mémoires Acad. R. Sci. (Paris), 1718, 274
———. 1722, Mémoires Acad. R. Sci. (Paris), 1722, 165
Marinoni, G. G., 1733, Nova Acta Eruditorum, 2, 278
Matsushima, S. 1967, PASP, 79, 178
Matsushima, S., & Zink, J. R. 1964, AJ, 69, 481
Matsushima, S., Zink, J. R., & Hansen, J. E. 1966, AJ, 71, 103
Maunder, E. W. 1921, J. Brit. Astron. Assoc., 31, 346
Mayer, T. 1752, Commentarii Soc. Reg. Sci. Gottingensis, 1, 379
Messier, C. 1772, Mémoires Acad. R. Sci. (Paris), 1772, 462
———. 1776, Mémoires Acad. R. Sci. (Paris), 1776, 441
———. 1783, Mémoires Acad. R. Sci. (Paris), 1783, 104
Messier, C. 1790, Mémoires Acad. R. Sci. (Paris), 1790, 442
Moore, P. 1963, Survey of the Moon (London: Eyre & Spottiswoode), 158
Newhall, C. G., & Self, S. 1982, J. Geophys. Res., 87, 1231
Planmann, A. 1762, Abhand. König. Schwedische Akad. Wiss., 24, 133
Poleni, G. 1729a, Philos. Trans., 36, 173
———. 1729b, Commentarii Acad. Sci. Imp. Petropolitanae, 4, 315
Poleni, G., & Morgagni, G. 1718, Giornale Lett. Italia, 31, 304
———. 1724, Philos. Trans., 33, 71
Robock, A. 2000, Rev. Geophys., 38, 191
Rodrigues, A. 1799, Memorias Acad. Real Sci. Lisboa, 2(2), 30
Rost, J. C. 1734, Miscellanea Berolinensia Increm. Sci., 4, 107
Russell, F. A. R. 1888, in The Eruption of Krakatoa and Subsequent Phenomena, ed. G. J. Symons (London: Truebner), 384
Schoenwald, S. T. 1754, Nova Acta Eruditorum Suppl., 7, 288
Schröter, J. H. 1794, Astron. Jahrbuch, 19, 120
Schröter, J. H., & Harding, K. L. 1801, Astron. Jahrbuch, 26, 193
Stothers, R. B. 1996a, Clim. Change, 32, 79
———. 1996b, J. Geophys. Res., 101, 3901
———. 2002, J. Geophys. Res., 107(D23), 4718
Strömer, M., & Wargentin, P. 1762, Abhand. König. Schwedische Akad. Wiss., 24, 122
Thordarson, T., & Self, S. 2003, J. Geophys. Res., 108 (D1), 4011
Toaldo, J. 1786, Saggi Cesareo-Regia Accad. Padova, 1, 265
Vassy, E. 1956, J. Scientifique Météorologie, 8, 1
Velho, J. A. 1799, Memorias Acad. Real Sci. Lisboa, 2(1), 512
Villas-Boas, G. de 1799, Memorias Acad. Real Sci. Lisboa, 2(1), 517
von Oppolzer, T. R. 1887, Canon der Finsternisse (Vienna: Imperial Acad. Sci.)
Wargentin, P. 1761, Philos. Trans., 52, 208
———. 1780, Nova Acta Soc. Sci. Upsaliensis, 3, 214
Weidler, J. F. 1729, Acta Eruditorum, 48, 442
Williams, S. 1785, Memoirs Am. Acad. Arts Sci., 1, 81
Wolf, N. M., 1781, Astron. Jahrbuch, 6, 81
Wollaston, F. 1785, London Mag. (New Series), 4, 161
Wurzelbau, J. P. 1710, Miscellanea Berolinensia Increm. Sci., 1, 242
Zach, F. X. von 1794, Astron. Jahrbuch, 19, 168
Zielinski, G. A. 1995, J. Geophys. Res., 100, 20937
Zielinski, G. A., et al. 1994, Science, 264, 948